Oxford Physics

UNIVERSITY OF OXFORD

Complete Spatial Characterisation of EUV Wavefronts

David Lloyd, Kevin O'Keeffe, Simon Hooker

EPSRC Engineering and Physical Sciences Research Council

Complete Spatial Characterisation of EUV Wavefronts

1. **Characterisation**
2. **Method**
3. **Results**
4. **Outlook**

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Characterisation

- Successful design and implementation of (optical) experiments requires knowledge of illuminating radiation.

- Beam characterization concerned with:
    - Transverse intensity profile
    - Transverse phase profile
    - Spatial coherence
    - Temporal pulse shape
    - Temporal coherence

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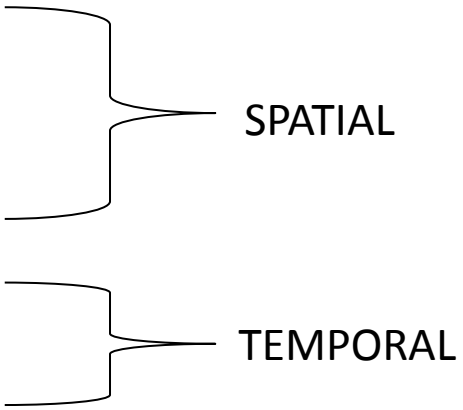


Spatial Properties

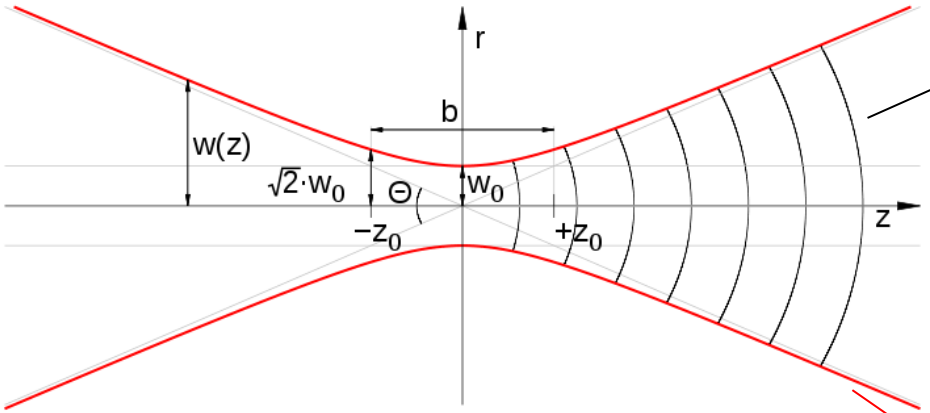


Diagram of a focussed gaussian beam.

Contour of equal phase – a diverging wave has a curved wavefront with a positive radius of curvature.

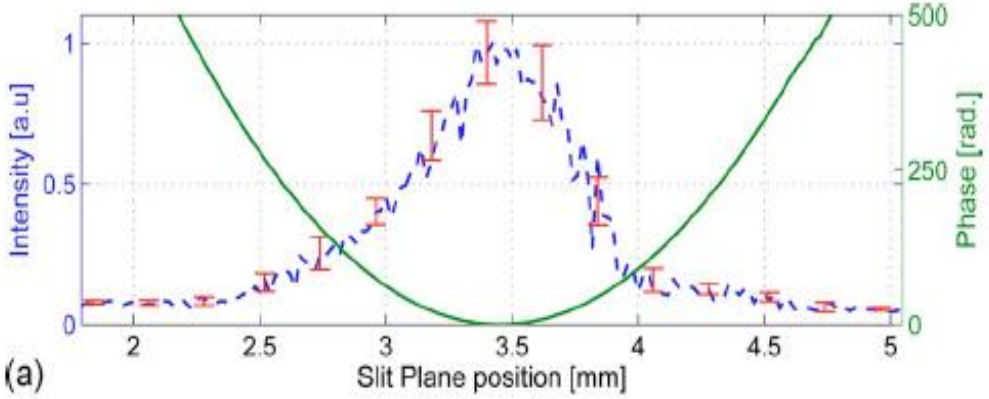
Intensity profile widens with increasing distance

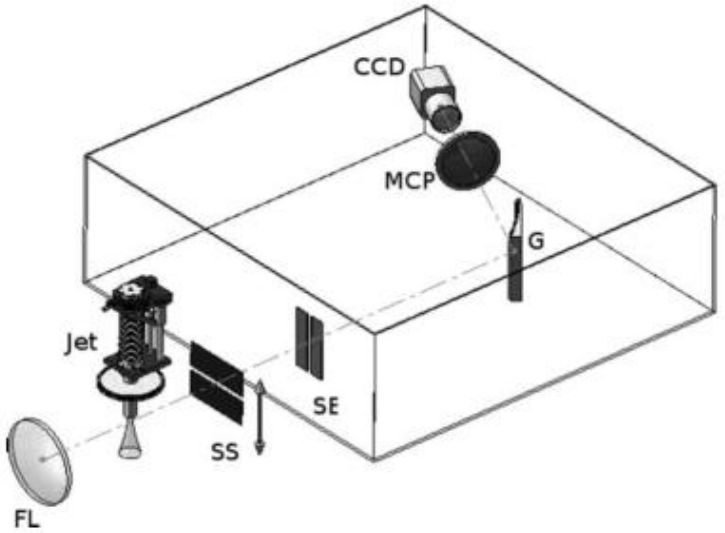
Space-time coupling may be present and is potentially detrimental to experiments.

Wavefront Characterization

SWORD

Spectral Wavefront Optical Reconstruction by Diffraction



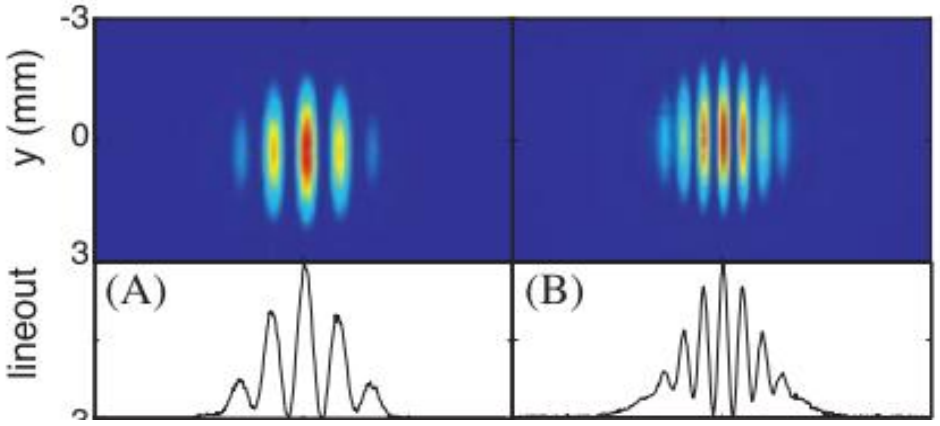


Images taken from [1]

- Scan thin slit transverse to propagation direction.
- Retrieve phase profile from centroid position.
- Retrieve intensity profile from transmitted flux.

[1] E. Frumker et al. Optics Letters, 34:19, 3026-3028 (2009)

Spatial Coherence



Interference fringes from fully coherent phase-matched high harmonic source. Figure taken from [2]

- Coherence defined by correlation by E-field at two separate locations $\langle E_1 E_2^* \rangle$
- Normalised correlation strength is called Complex Degree of Coherence (γ) and is related to fringe visibility (v) through:

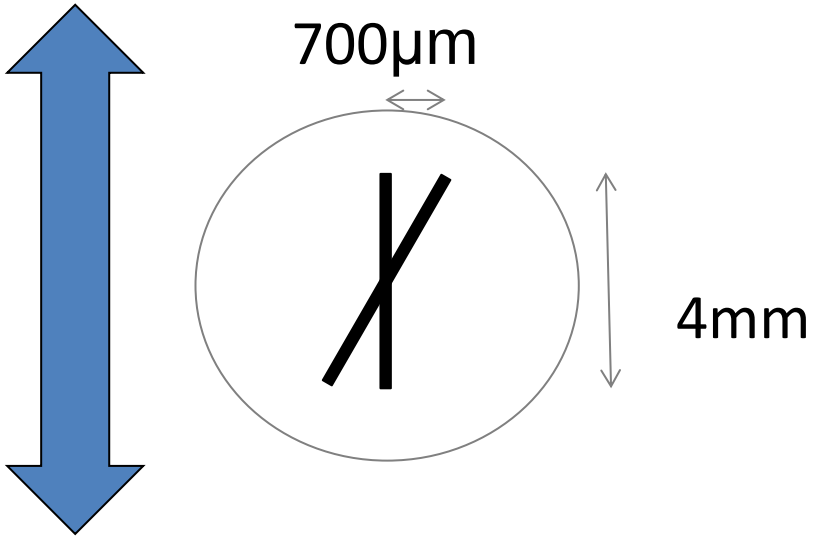
$$V = \frac{2\sqrt{I_1}\sqrt{I_2}}{I_1+I_2}|\gamma|$$

Our technique measures the wavefront and coherence simultaneously.

[2] R Bartels, et al. Science. 297(5580):376 (2002)

Complete Characterisation

SCanning Interference Measurement for Integrated Transverse Analysis of Radiation [4]



- Scan slit in vertical position – continuous change in pinhole separation.
- Incident beam intensity, phase and spatial coherence are retrieved from interference patterns.

[4] Lloyd et. al. *Optics Letters*, *38*(7), 1173. (2013)

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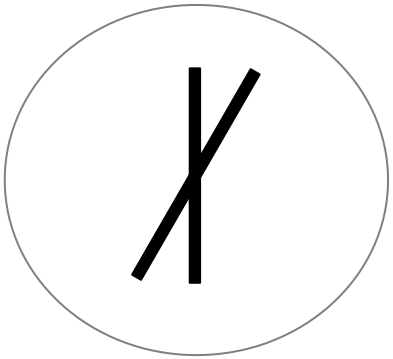

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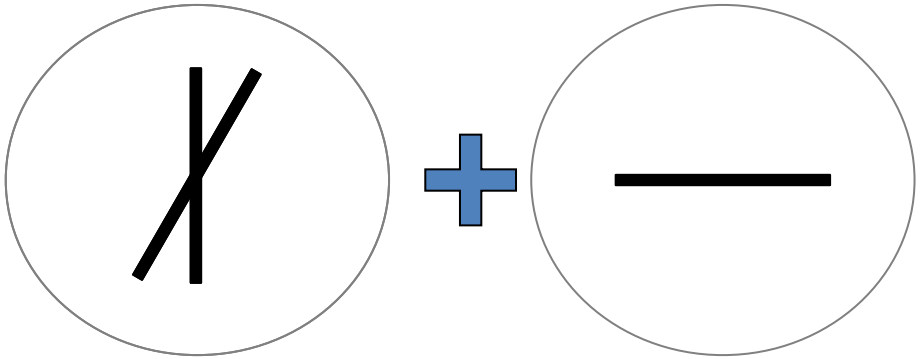

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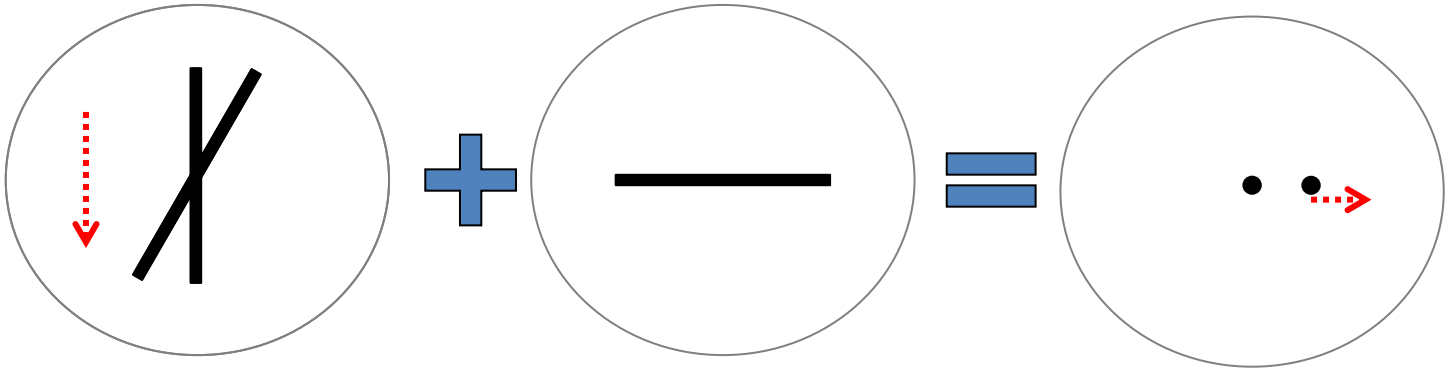

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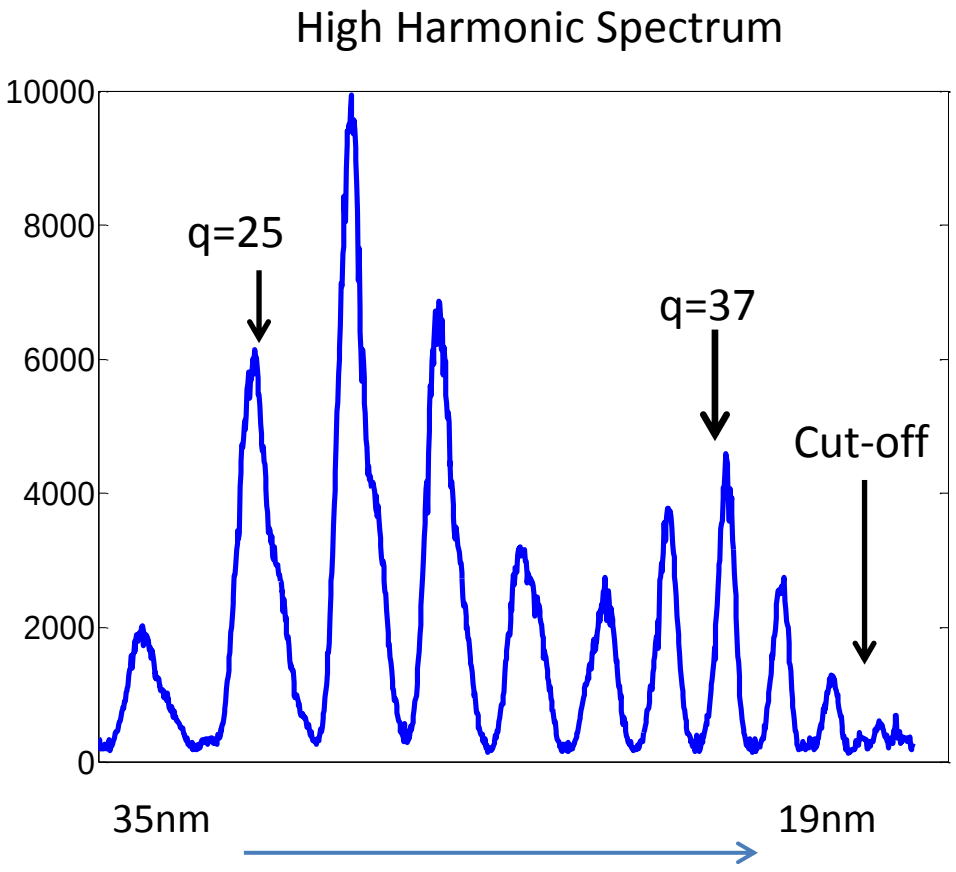
High Harmonic Generation

- Table-top source of EUV/soft x-ray radiation.
- Intense pulses from a (commercial) Ti-Sapphire laser are focused into a noble gas.
- Non-linear interaction produces a frequency comb extending to an abrupt cut-off.
- Odd multiples of laser frequency (harmonic order labelled by q).

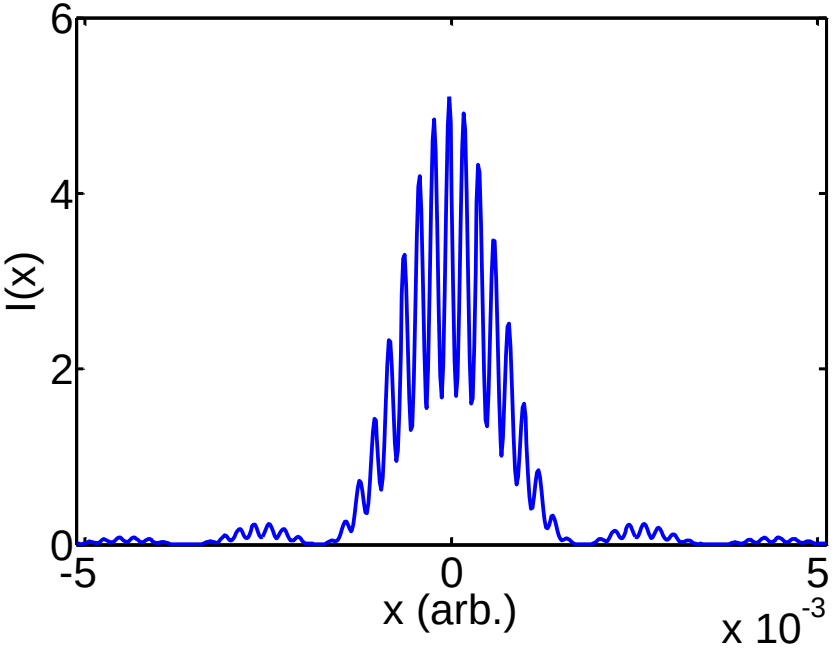


Interference Analysis

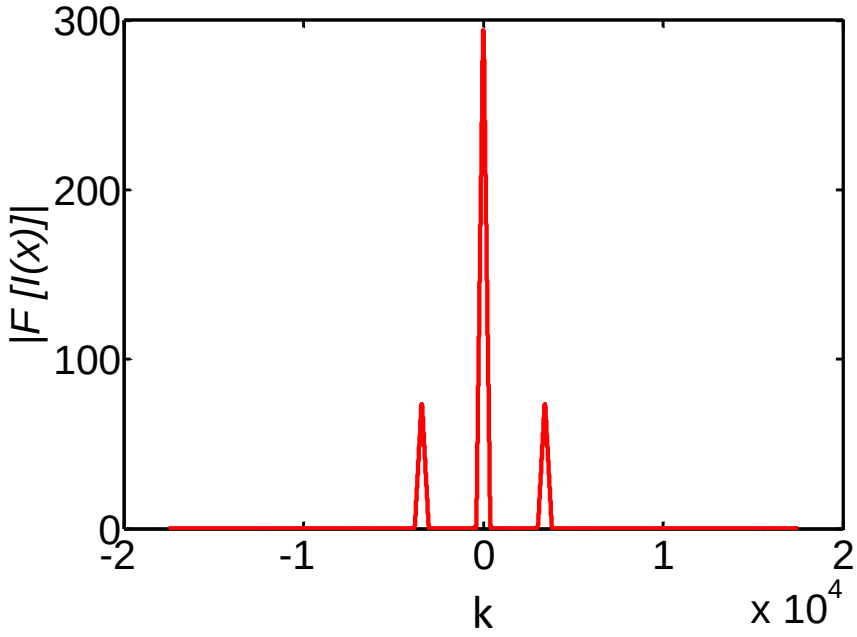
Interference pattern from pinholes has the form:

$$\boldsymbol{I(x) = \varepsilon(x)[1 + V\cos(k_0 x + \varphi)]}$$

$$\boldsymbol{\varepsilon(x) \propto (I_1 + I_2)}$$



FFT



[5] Takeda et. al. JOSA, Vol. 72, Issue 1, pp. 156-160 (1982)

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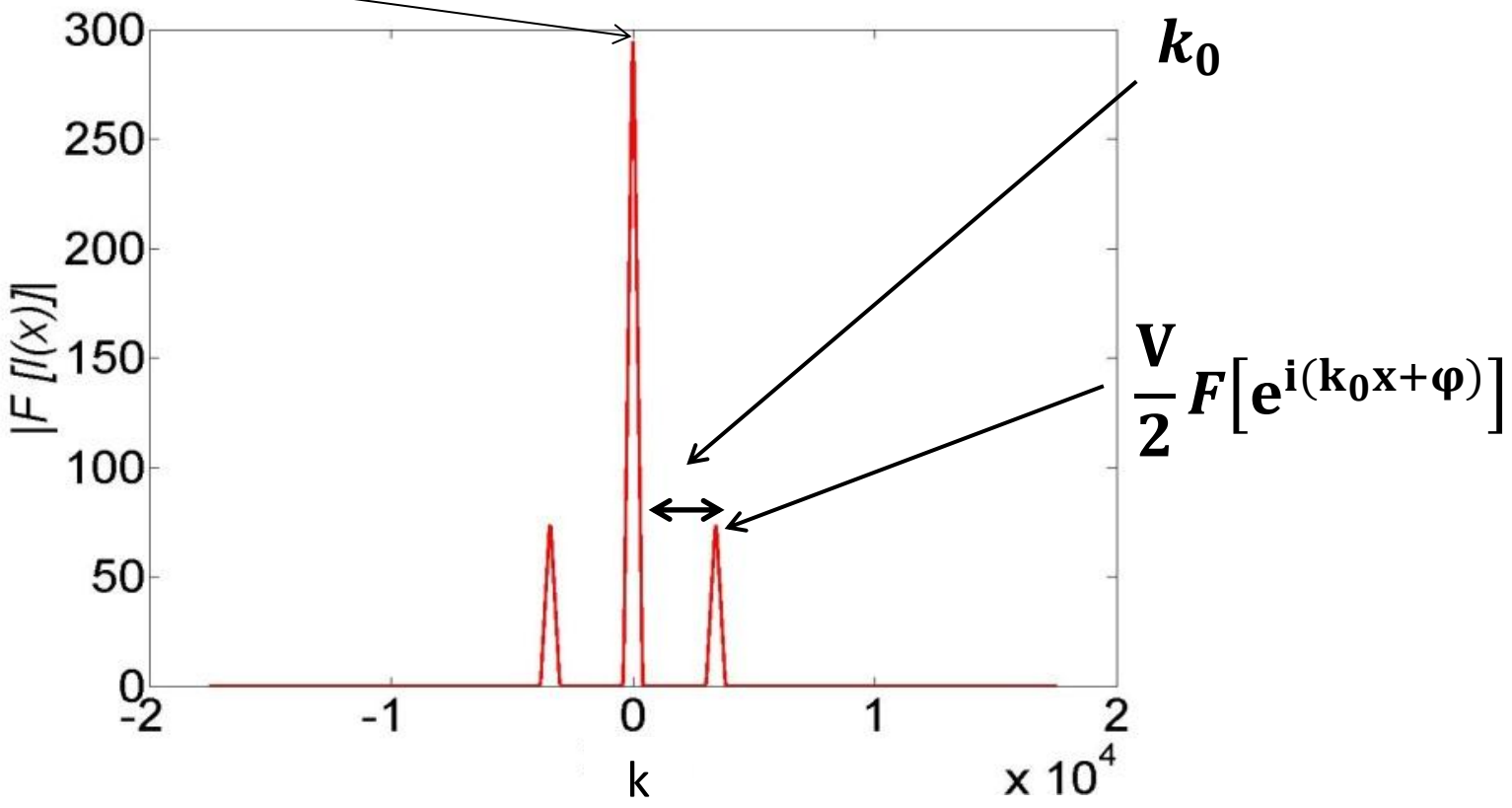

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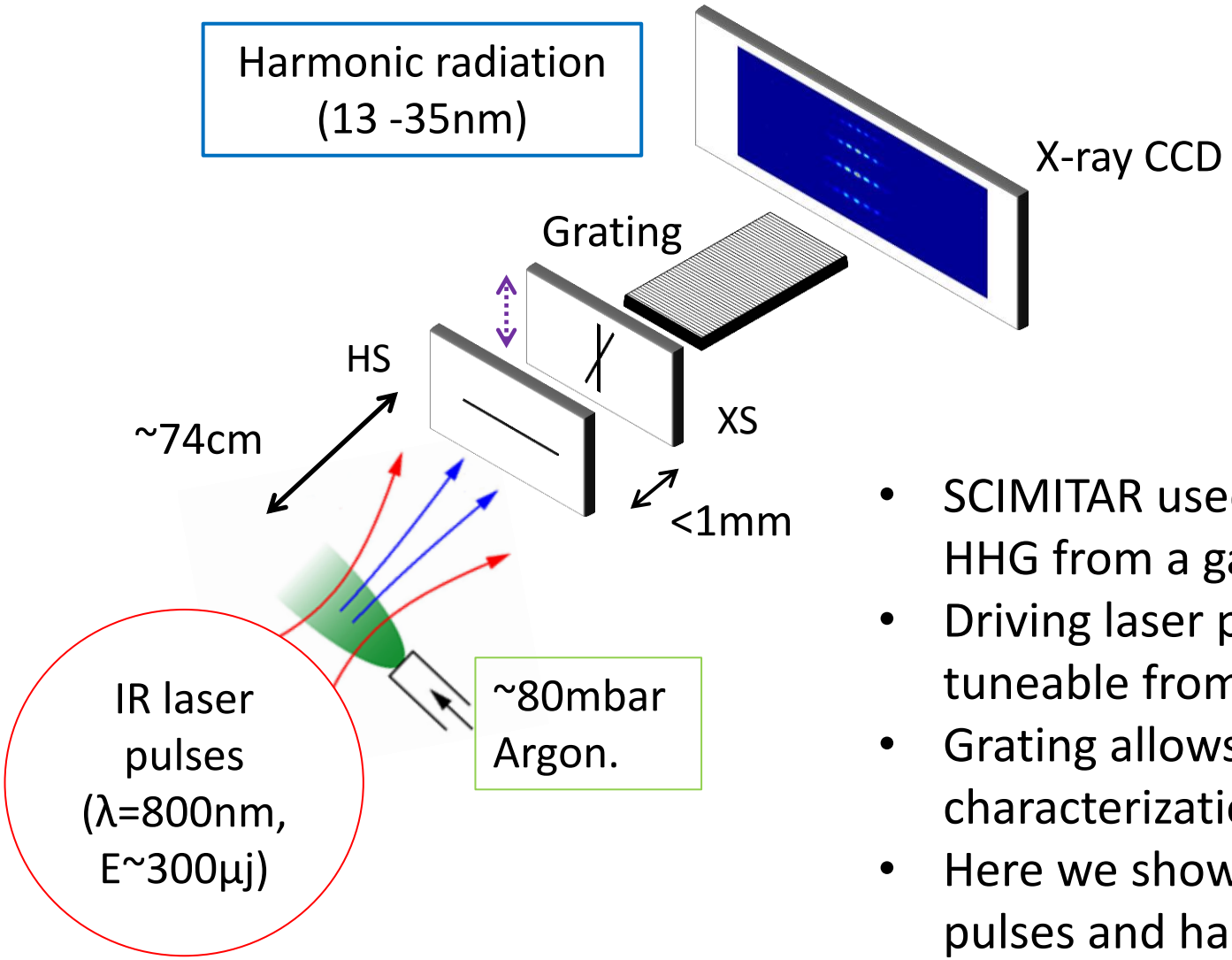
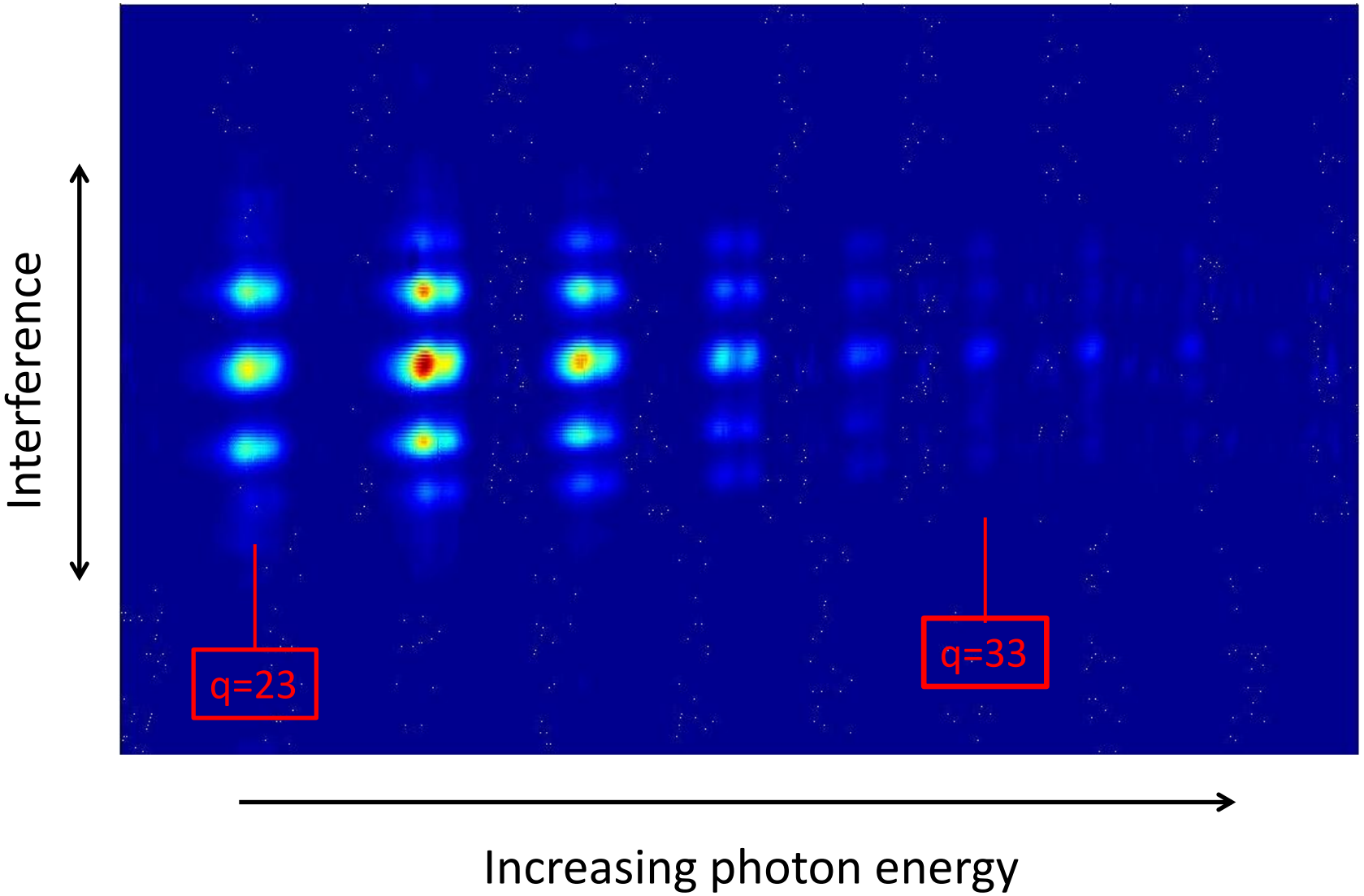
Experimental Demonstration

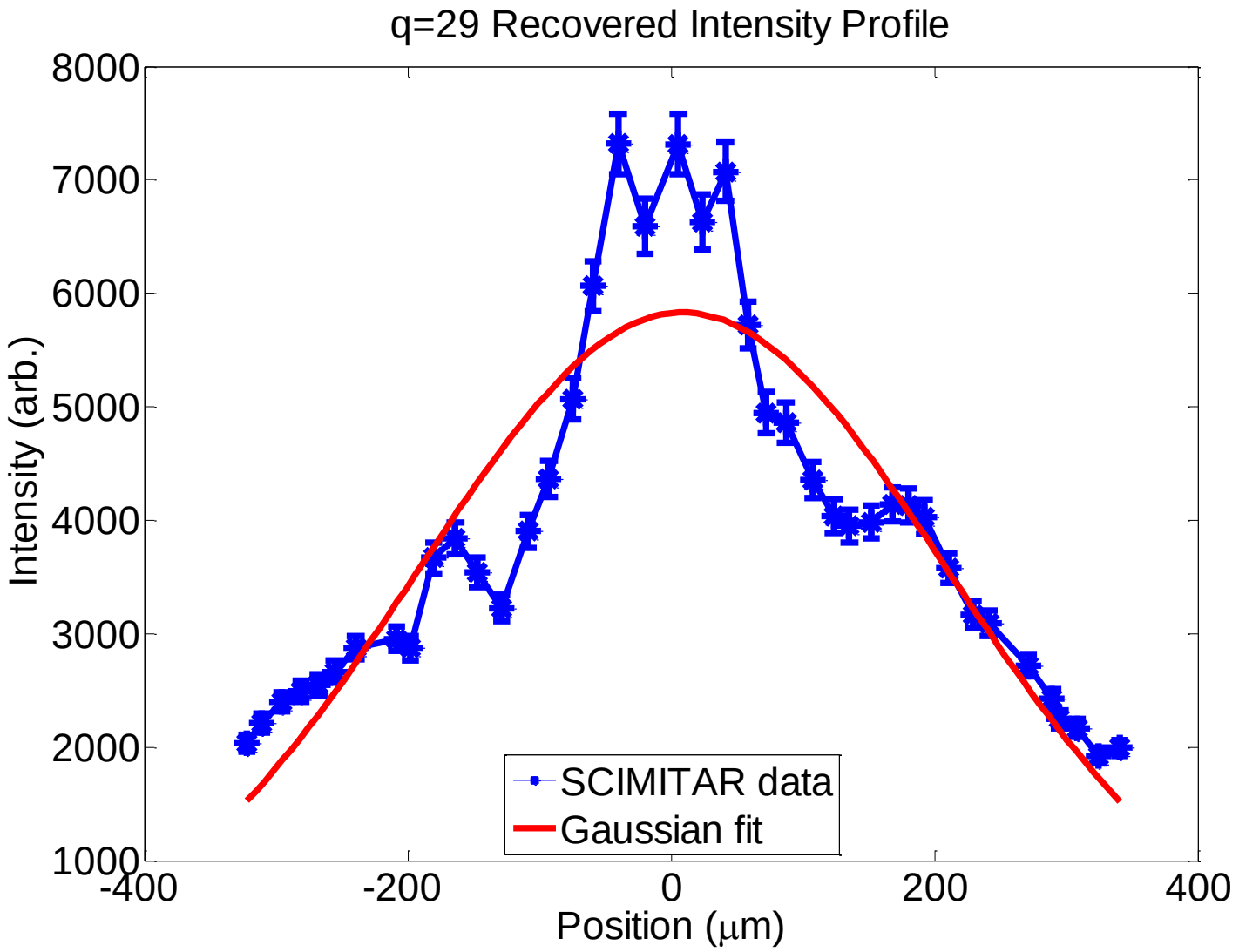


- SCIMITAR used to characterize HHG from a gas cell.
- Driving laser pulse duration tuneable from 12-50 fs.
- Grating allows spectrally resolved characterization.
- Here we show results for 22fs pulses and harmonic orders up to q=33.

Example Acquisition



SCIMITAR - Intensity



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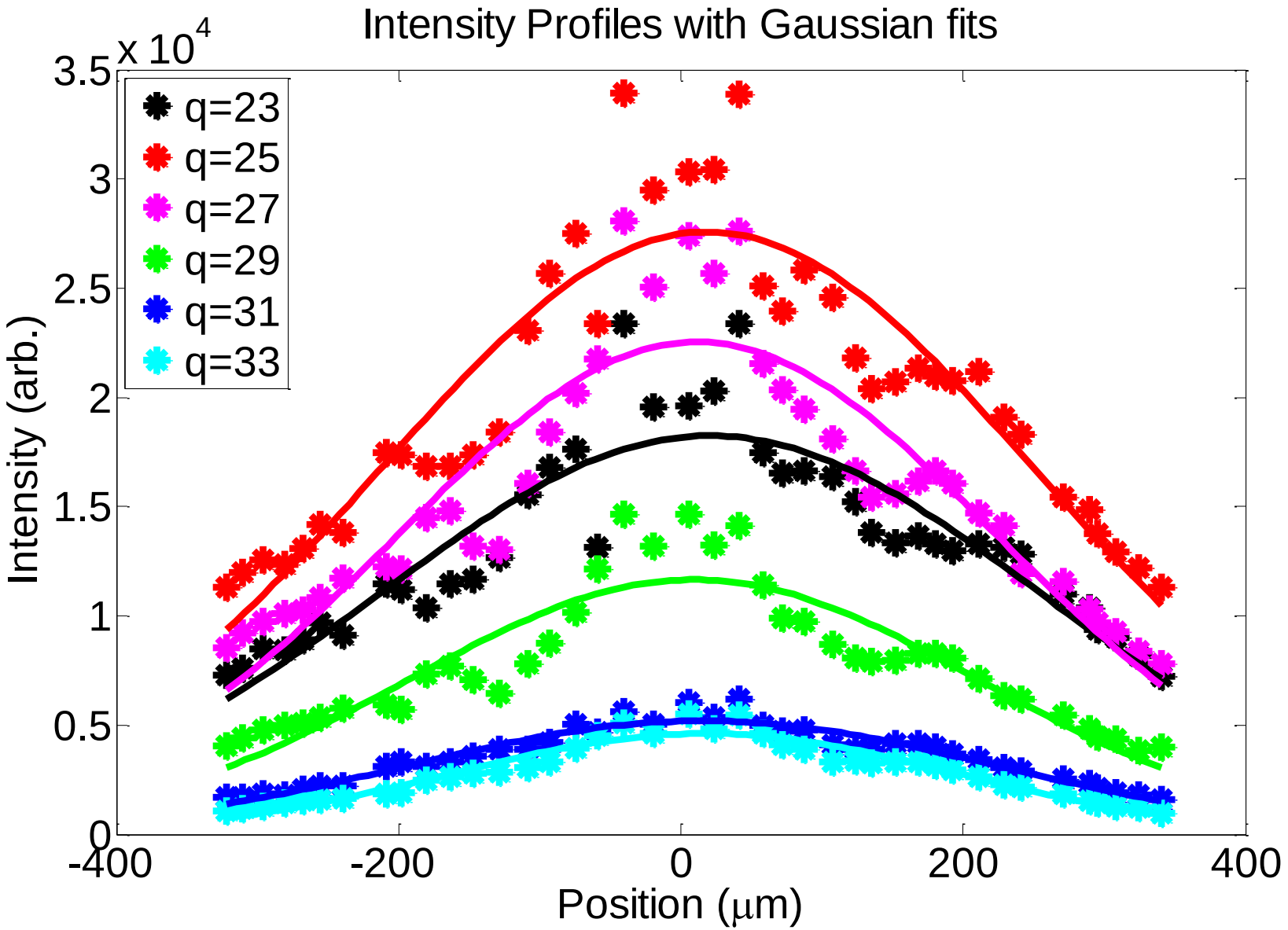
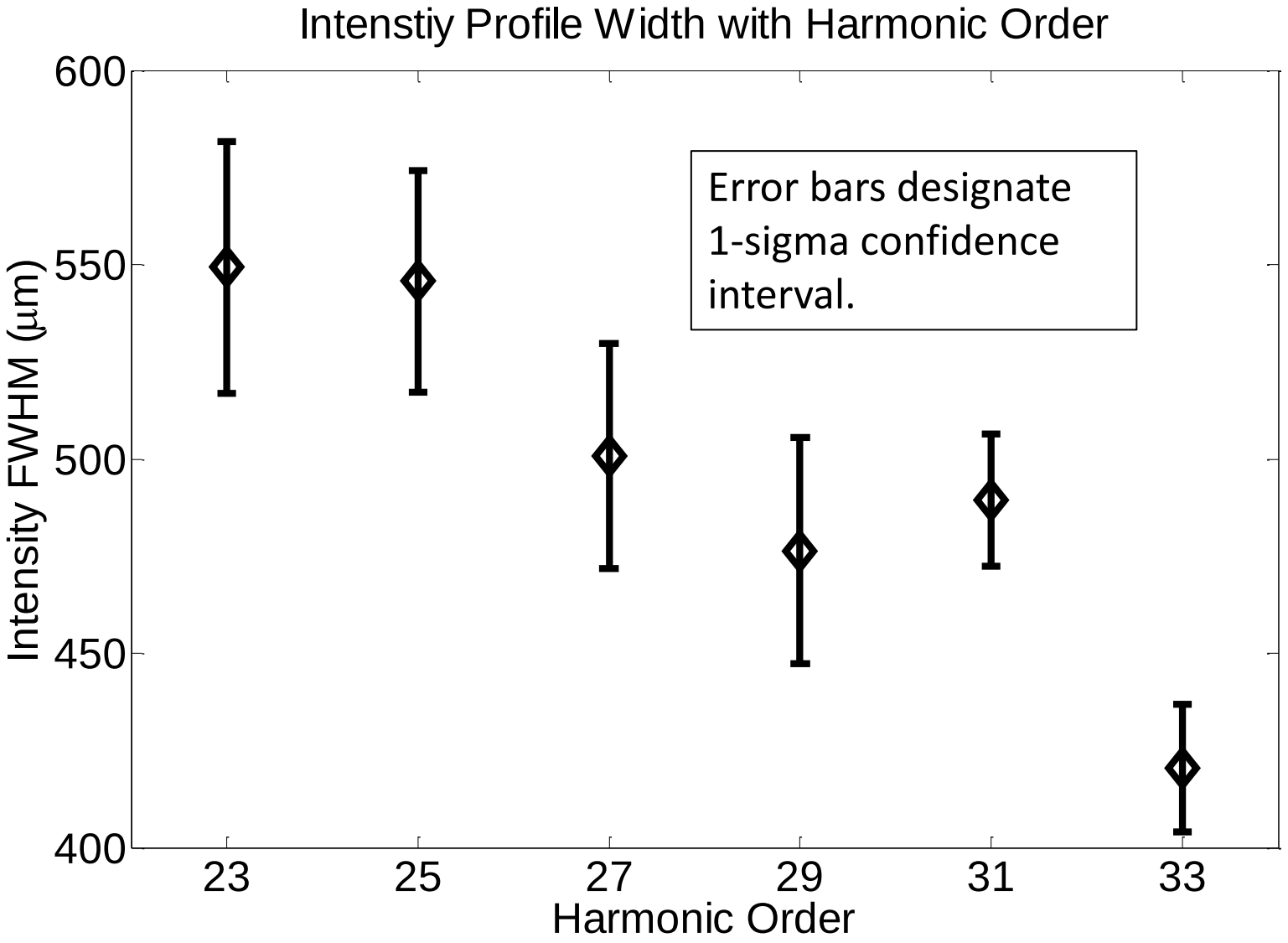
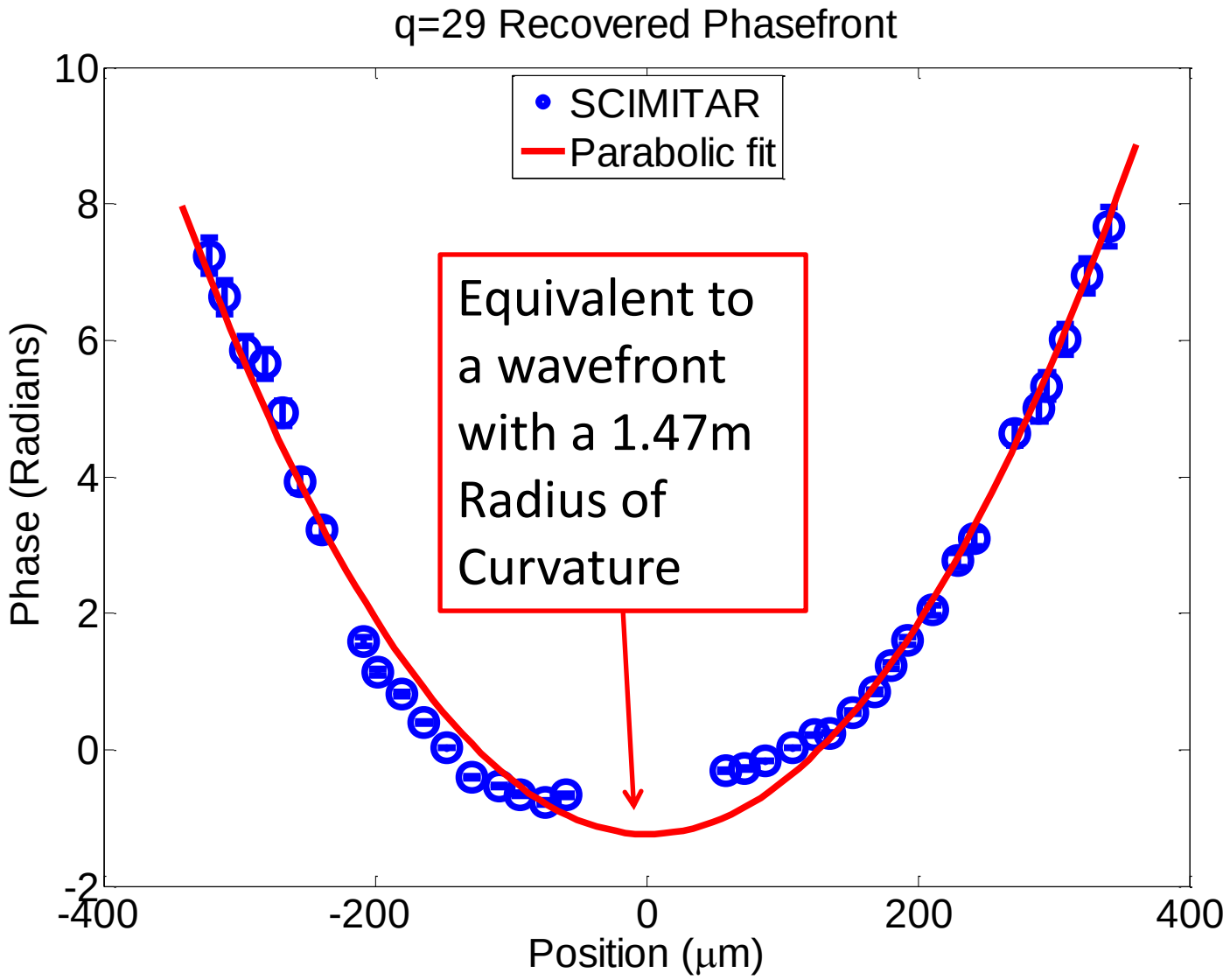


SCIMITAR - Intensity



SCIMITAR - Phase



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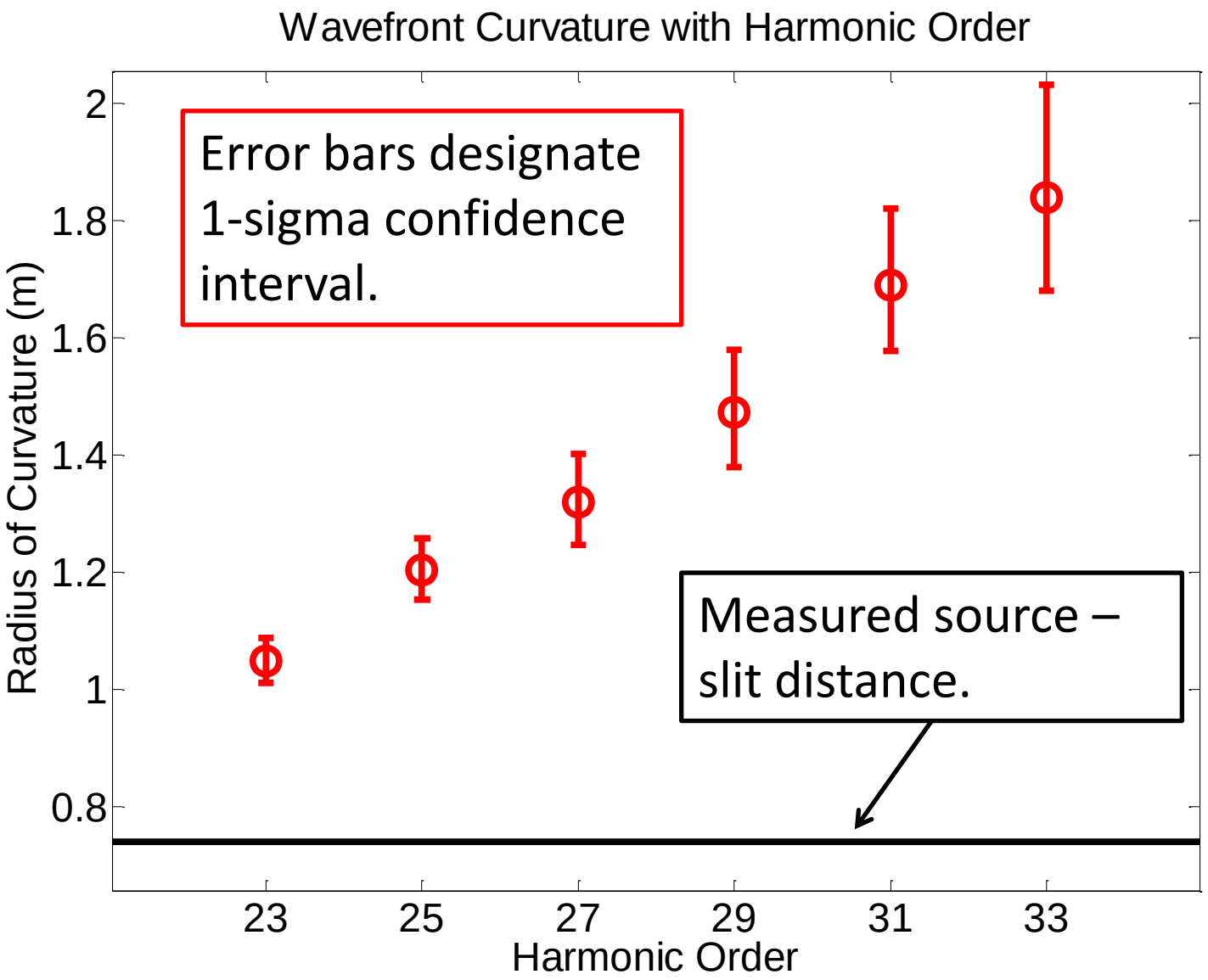
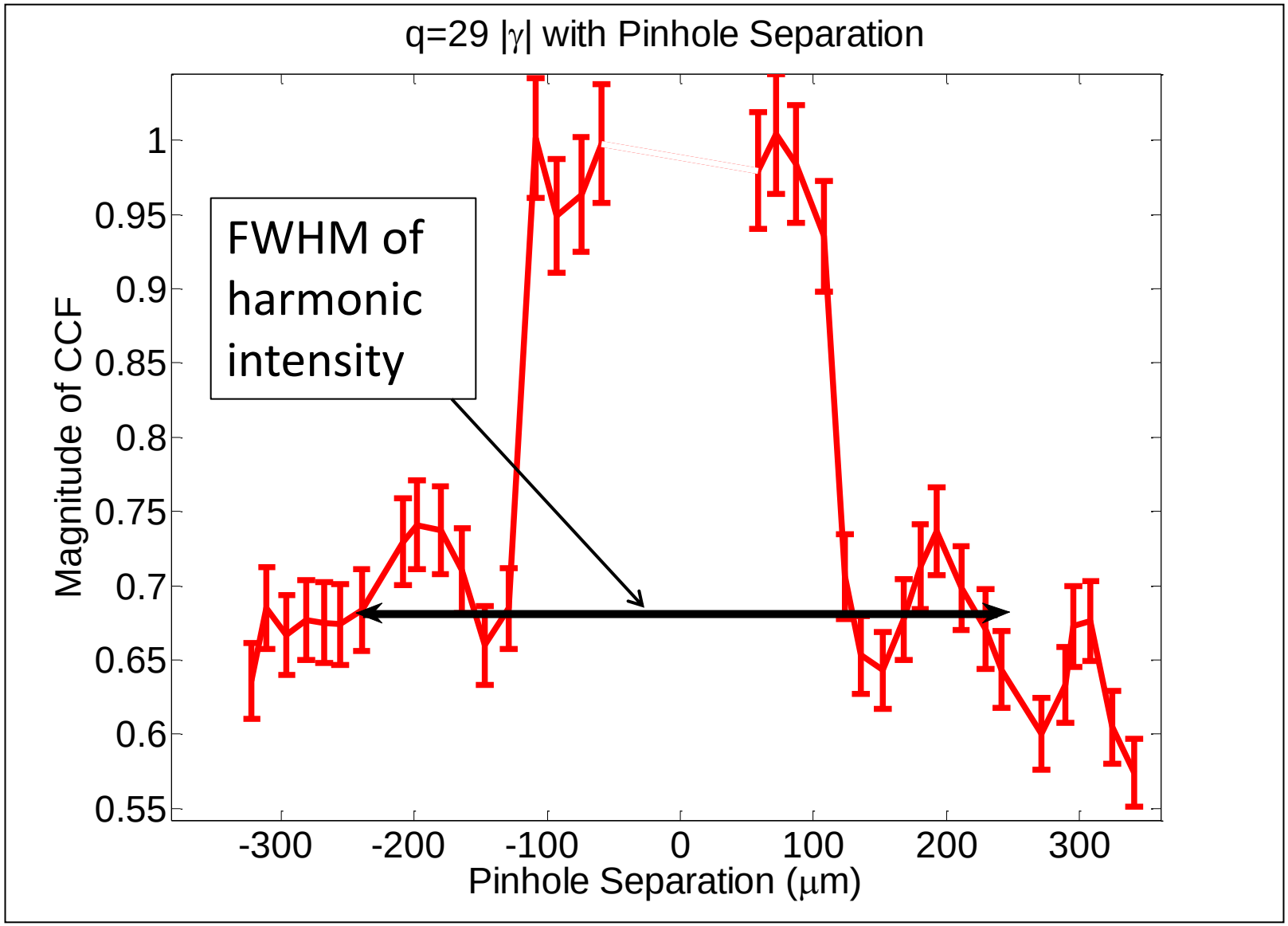


SCIMITAR – Spatial Coherence



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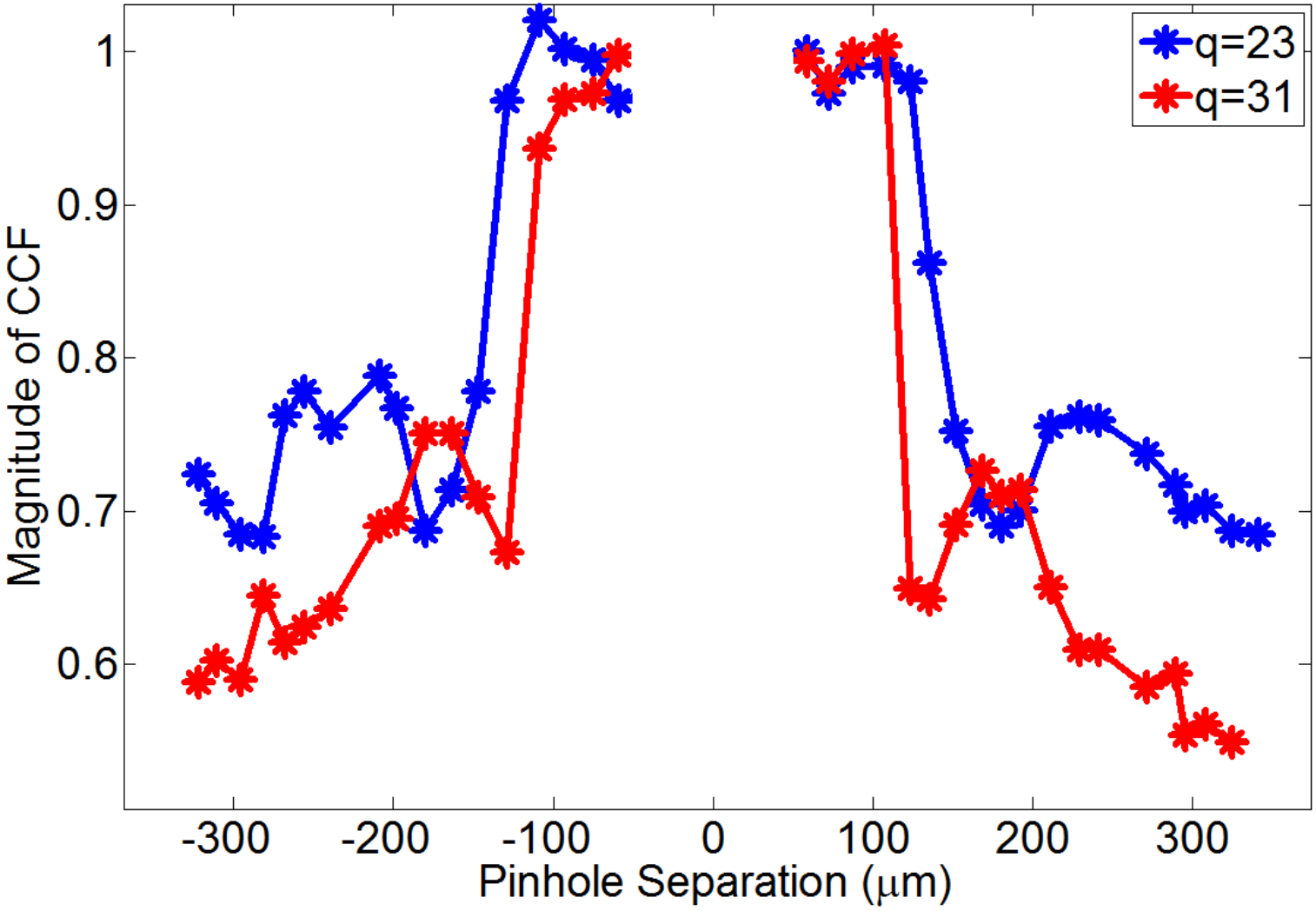
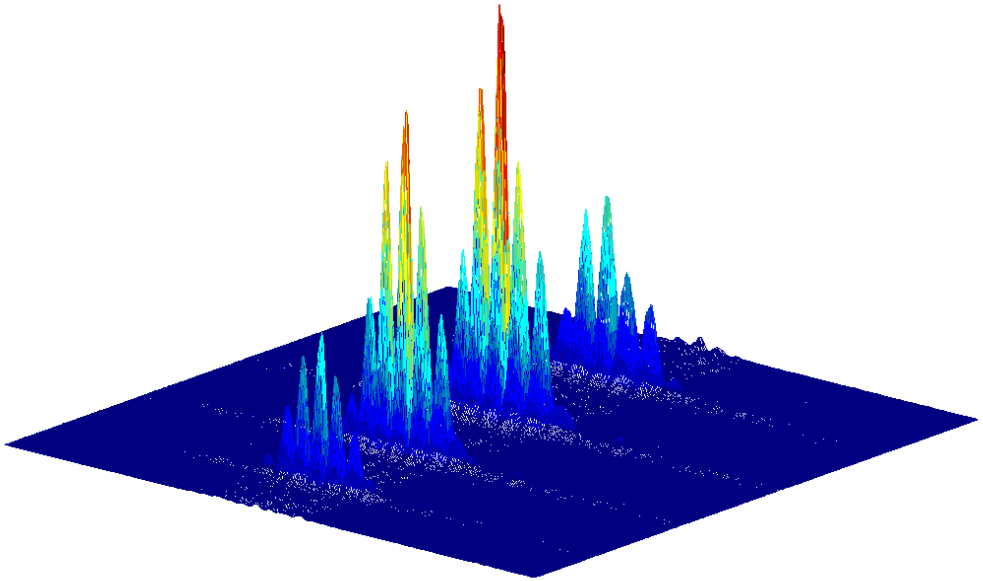


Summary

- SCIMITAR simultaneously retrieves:
  - Transverse intensity profile
  - Spatial phasefront
  - Spatial Coherence left-right of beam centre

- SCIMITAR is applicable to a wide range of light sources.
- We have demonstrated the technique by characterizing HHG.



Future Work

- Relate results to full theory of partially coherent diffraction (c.f Gaussian – Schell model).

Thank you

EPSRC Engineering and Physical Sciences Research Council

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Incoherent Radiation

Two pinhole "interference" from an incoherent wavefront:

$$I(X) = I_1 \mathrm{Sinc}\left(\frac{kXa}{2z} + \frac{a}{2}\frac{d\varphi}{dX}\Big|_0\right)^2 + I_2 \mathrm{Sinc}\left(\frac{kXa}{2z} + \frac{a}{2}\frac{d\varphi}{dX}\Big|_s\right)^2$$

- Gradient in phase extracted from patterns (similar to SWORD).
- Integrate across transverse direction to retrieve phasefront.
- In this scenario, there is no benefit of using SCIMITAR over SWORD.